

A TRANSIENT FINITE ELEMENT STUDY REVEALS THE IMPORTANCE OF THE BYCICLE HELMET MATERIAL PROPERTIES ON HEAD PROTECTION DURING AN IMPACT

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Abstract:

This paper is focused on understanding the mechanism that gives the bicycle helmet the role of protecting the head during an impact. The finite element method is used here as a first step in the helmet optimisation and improvement process. The relation between different helmet mechanical parameters and the risk of head injury during the impact is described using MSC Marc Mentat finite element software. The reduction in resulting head linear acceleration by more than 80% and in resulting stress by more than 65% prove the protective effect of all materials studied with an indication of superior behaviour for the anisotropic foam.

Keywords: finite element analysis, bicycle helmet, anisotropic foam, linear acceleration, stress, deformation.

PEDAL CYCLING REPRESENTS ONE OF THE MOST POPULAR RECREATIONAL SPORTS, but also one of the main transportation means all over the world. In 2000, road traffic injuries caused the death of an estimated number of 1,200,000 humans, representing the ninth highest cause of death worldwide (United Nations, 2003). In Belgium a total of 6655 injuries and 134 fatalities due to cycling accidents were registered on public roads in 2000, with 9.8% of all road accidents and 9.1% of road traffic deaths being represented by pedal cyclist (NIS, 2000). Moreover, 21 to 61% of the bicycle accidents victims seeking medical care have a head injury (Collins, 1993; Eilert-Petersson, 1997) and 69–93% of fatal bicycle accidents are due to the head injuries (Guichon, 1975; Oström, 1993). Most of these victims were not wearing a helmet. The nowadays available helmets might have prevailed the injury. However, helmets design and material can be improved (McIntosh, 1995; Ching, 1997). Previous research work in our interdisciplinary group indicates the use of anisotropic foams as appropriate for achieving this goal (Depreitere, 2004, 2007; Van Lierde, 2005).

The aim of this paper is to assess the influence of different foam material properties and geometrical parameters on the helmet's protective capability under different impact conditions by using finite element simulations. More in particular, the goal of the study is to investigate whether the degree of protection offered by the helmet effectively can be improved by using foam liners with optimized material properties.

METHODOLOGY:

FINITE ELEMENT MODELS DESIGN: The models were designed starting from the .STL (standard triangulate language) file of an adult bicycle helmet with air vents (figure 1A) and from the .STL file of an adult dummy head using Mimics® and Magics® (Materialise, Haasrode, Belgium). This type of helmet assures a better coverage of the head temporal area (Depreitere, 2004). In order to evaluate the influence of some geometrical parameters, another solid helmet version was built by filling the vents (figure 1B). The external shell was created in MSC Marc by applying a uniform offset of 0.25mm to the external surface of the foam liner. Therefore, both solid assemblies assume an internal foam liner of ~20 mm and a uniform external shell of 0.5 mm, with an intimate contact between components. Through a registration process the best fit between the components and the best head position relative to the helmet is achieved. The solid meshes are obtained in MSC.Patran® using the 4-node linear isoparametric tetrahedral elements with ~6 mm edge size.

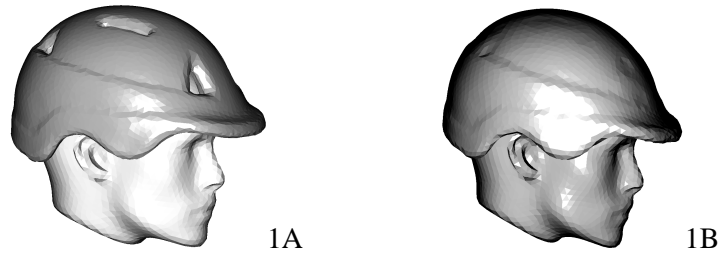


Fig.1: The child type helmet models – with (1A) and without vents (1B)

FINITE ELEMENT IMPACT SIMULATIONS: The MSC Marc Mentat software is used for both processing and post-processing phases. The finite element simulations reproduce a free fall of the assembly on a rigid surface. An initial velocity of 5.23 mm/s is applied to all the bodies so that the impact velocity corresponds to a fall from 1.5 m. The gravitational acceleration (9.8mm/s^2) is active during all the simulations. The simulation time of 0.025s allows only short impact durations.

For each of the two geometries four models are built so that the dynamic behaviour of all material types listed in table 1 can be observed. The polyether sulphone foam is assumed to have an elastic-plastic transversally isotropic material behaviour. All types of expanded polystyrene (EPS) are considered isotropic elastic-plastic materials (Zhang, 2004). Linear elastic and isotropic material properties are assigned to the shell (polycarbonate PC) and to the head form (standard crash dummy head - Duraluminium material properties). All material properties used in the simulations are reproduced in table 1. Two pairs of links are used to simulate the straps with a stiffness coefficient of 10. The influence of foam-shell interface contact conditions is observed by reproducing two different situations: a glued contact and a frictionless sliding contact. For all the other interfaces a sliding contact is assumed.

Table 1: Material properties used in the finite element models

Material properties Type of material	Young Modulus (E) (MPa)		Shear Modulus (G) (MPa)		Poisson ratio (v)		Density (ρ) (g/mm ³)	Yield stress (MPa)
Polycarbonate	2000		-		0.37		$1.12 \cdot 10^{-3}$	-
Head	2500		-		0.3		$1.247 \cdot 10^{-3}$	-
EPS high density (HD)	19.88		-		0.17		$58.15 \cdot 10^{-6}$	20
EPS medium high density	15.75		-		0.14		$50.98 \cdot 10^{-6}$	15
EPS medium density	10.05		-		0.11		$39.85 \cdot 10^{-6}$	10
PES	E ₁	0.55	G ₁	0.5	v ₁	0.1	$57 \cdot 10^{-6}$	0.55
	E ₂	0.55	G ₂	3	v ₂	0.1		0.55
	E ₃	23	G ₃	3	v ₃	0.1		20

RESULTS: When the helmet impacts the rigid surface, only a few nodes of the elastic shell initially come into contact. Soon these nodes gain a velocity in the opposite direction while still maintaining the contact with the rigid surface.



Fig. 2: Solid views showing the foam layer deformation caused by the impact (right) compared with the initial situation, before the impact occurs (left)

After the head contact the helmet, the nodes of the shell, which are in contact with the rigid surface, acquire again velocity in the direction of the impact and the contact force between the shell and rigid surface increases. The maximum foam deformation takes place during this phase (0.005s - 0.01s). The foam thickness reduction due to this deformation is ~80% in the impact zone (figure 2). After the contact force reaches a maximum, the helmet starts rebounding. Due to the helmet sliding on the rigid surface the contact force at this interface drops again (0.01s - 0.015s). The head and helmet separate again and the contact force at this interface drops (0.015s - 0.025s).

All types of EPS studied show a similar trend in terms of von Mises stress and linear acceleration with two main peak regions that are related to the impact dynamics described above (figure 3). In the case of PES the peak values are obtained in the initial phase of the impact and decrease during the main deformation phase (figure 3). For the same impact conditions, there is more than 85% reduction in the maximum linear acceleration and more than 65% reduction in the maximum von Mises stress of the helmeted head for all types of materials studied when compared with the values obtained for the non-helmeted head (figure 3).

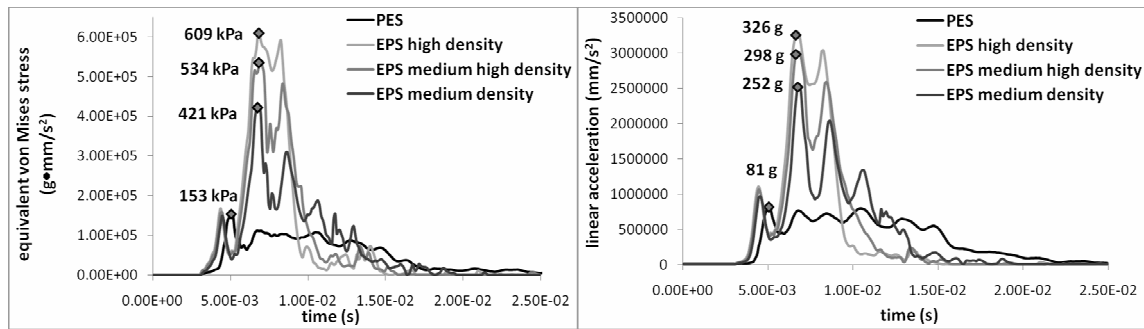


Fig. 3: The evolution of Von Mises stress (left graph) and linear acceleration (right graph) plotted in the head center during the impact for all materials considered in the simulations

Considering a frictionless sliding shell-foam interface the FE simulations results indicate a decrease in head linear acceleration by ~31% and von Mises stress by ~27% when compared with the case where the components were glued (figure 4).

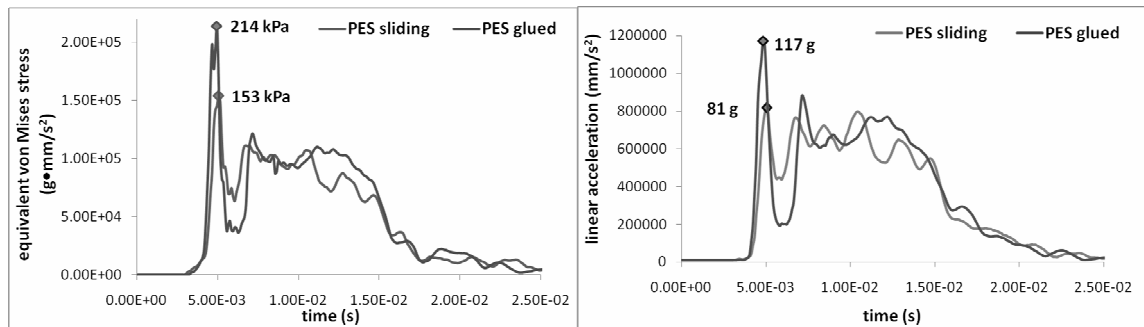


Fig. 4: The evolution of Von Mises stress (left) and linear acceleration (right) plotted in the head center during the impact for two shell-foam interface conditions: sliding vs. glued contact

DISCUSSIONS AND CONCLUSIONS: This study evaluates the protective mechanisms of different types of helmets in vertical impact conditions. The influence of the foam material properties and design (vents, interface conditions) on the stress distribution and on the impact energy transmission to the head is studied. By considering the head as a deformable body an external map of the stress distribution and evolution during the impact is obtained. The contact forces and stresses following the impact for the helmeted head are compared with those of a non-helmeted head.

Bicycle helmets are primarily designed to reduce the effect of linear forces by providing a soft

crushing layer, which reduces the peak linear acceleration of the head and brain during the impact. The current safety standards specify that the peak forces of acceleration must not exceed 300g for CPSC and Snell B95 and 250g for EN 1078 and the Australian Standard. The peak linear acceleration values obtained in this study for all types of expanded polystyrene indicate that these helmets might not provide optimal protection against all head injuries. This study shows a superior material behaviour for the anisotropic PES foam compared to the different expanded polystyrene foam densities. The PES reduces both stress and linear acceleration transmitted to the head. The values obtained from the simulations are in a range that fit the profile of the safety standards mentioned above. The PES foam shows a better behaviour in terms of head protection by reducing the head stress by ~70% and the linear acceleration by more than 95% when compared with a non-helmeted head impact.

Moreover, by introducing a frictionless interface between shell and foam, an important reduction in linear acceleration and stress can be obtained. Furthermore, the relation between the vents location and the stress distribution into the helmet must be considered as very important. This factor together with the material properties influences the stress propagation and the foam crushing behaviour. This leads to an inherent influence on the energy absorption process.

Many previous studies have outlined the effectiveness of using bicycle helmets (Thompson, 1989; Thomas, 1994). However, we have to consider that no helmet can protect against all possible impacts, and that death or serious injury still can happen. Further investigations are needed in order to completely describe the helmet protective behaviour. The future work will focus on describing the helmet protective effect against rotational acceleration when subjected to an angular impacts.

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